

Efficiency of spin-injection terahertz oscillator

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Abstract

Energy efficiency in terahertz range is evaluated experimentally of a spin-injection oscillator based on a ferromagnetic rod-film structure with point contact between the components. Choice of the film material influences substantially the efficiency. A magnetic flux concentrator is used to improve the efficiency. It is found from the measurements that the quantum efficiency can exceed unity. The latter indicates substantial contribution of stimulated radiative transitions.

1 Introduction

Investigations and applications of terahertz (THz) radiation evoke increasing interest. Such a radiation interacts softly with biological objects without radiative damage, it is suitable for nondestructive diagnostics, it spans actual range of a wide class of internal particle motions in materials, that makes it possible to study material structure and properties, to miniaturize sizes and weight of the local communication devices, etc. [1]. Broad use of THz devices is hindered nowadays because of absence of compact and reliable sources. A frequency converting method is used that is cumbersome and low-effective [2, 3].

Recently, an idea has been proposed of a laser-type coherent THz oscillator based on spin-polarized current through a magnetic junction [4, 5]. However, some problems of principal and technological character appear in attempts of realizing the idea [6, 7]. To overcome the problems, new types of layered structures were proposed with a point contact between conducting ferromagnetic rod and very thin ferromagnetic metal film.

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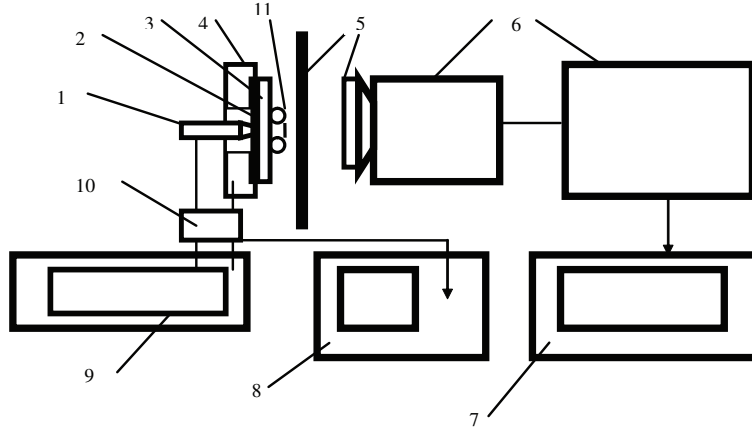


Figure 1: Scheme of the experimental set. The block numbers are explained in the text.

Such structures were realized and tested. Calculations show possibility of reaching very high current density $\sim 10^7\text{--}10^9$ A/cm² without damage and overheating [8]. The experiments confirmed these estimates [8, 9]. Besides, a possibility was predicted theoretically of reaching negative effective spin temperature and generation of THz radiation [9]. Recently, spin-injection driven THz radiation has been observed [10].

In this work, the results are presented of experimental study of integral energy characteristics of the radiator and the construction described in [10]. Also, attention is paid to estimates of the radiator quantum efficiency based on the measurements.

2 The experimental set

The measurements were carried out with experimental set shown in Fig. 1. The radiator consists of a sharpened steel rod 1, ferromagnetic film 2 deposited onto a dielectric substrate 3 transparent in THz range, and an electrode 4 closing the electric circuit. The signal passed through the substrate was recorded with power meter based on a Golay cell 6. The THz range is determined by means of two filters 5, namely, a low frequency filter of a metal grid with 125×125 μm^2 meshes and a TYDEX polymer high frequency filter. The radiator operating parameters (current and voltage) were recorded by a digital oscillograph 8, and the radiation power by a digital recorder. A dc source was used which supplied operating current up to 1 A. A resistance block 10 protected the power source 9 against overload under circuit shorting and formed signals in measurements. In some experiments, a magnetic field concentrator 11 was used.

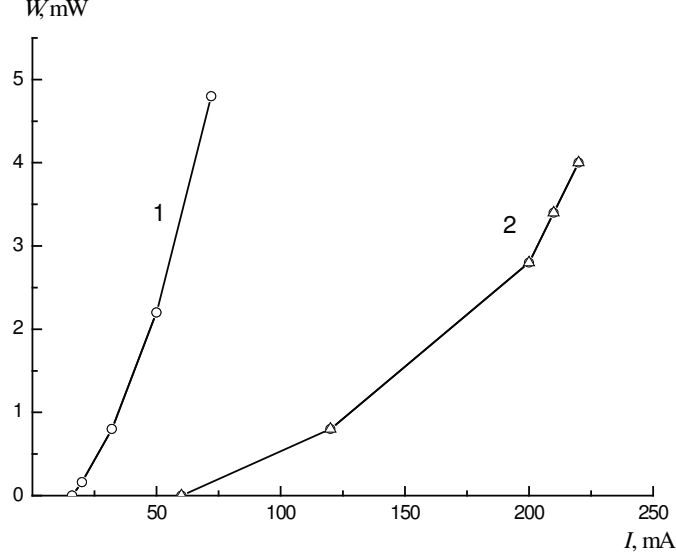


Figure 2: The radiation power as a function of the current: 1 — with Fe_3O_4 film, 2 — with Permalloy film.

3 The role of material

Epitaxial ferromagnetic films of two types were grown on the r plane of single crystalline sapphire by pulsed laser evaporation, namely, polycrystal Permalloy (Py) films 30 nm thick and epitaxial magnetite (Fe_3O_4) films 250 nm thick. Epitaxial Fe_3O_4 film was grown at 340°C on a sapphire ($\text{Al}_2\text{O}_3(-1012)$) with $\text{MgO}(001)$ underlayer 10 nm thick by laser evaporation of a Fe target in molecular oxygen at 9×10^{-5} Torr pressure. The radiator with the films indicated was studied. The radiation power as a function of the current is shown in Fig. 2. The curves 1 and 2 correspond to radiator with Fe_3O_4 and Py films, respectively. The maximal values of the currents in the experiments were restricted with breakdown in the film to rod contact. It is seen that the maximal radiation power was about 5 mW for both curves. However, to reach such a power, half as large current is required with Fe_3O_4 film, as with Py film. It is interesting to compare corresponding starting current values needed to observe radiation. It appears that the starting current is three times less with using magnetite film in comparison with Py film. It shows that magnetite allows more effective operation of the radiator than Py. We consider this with more detail below.

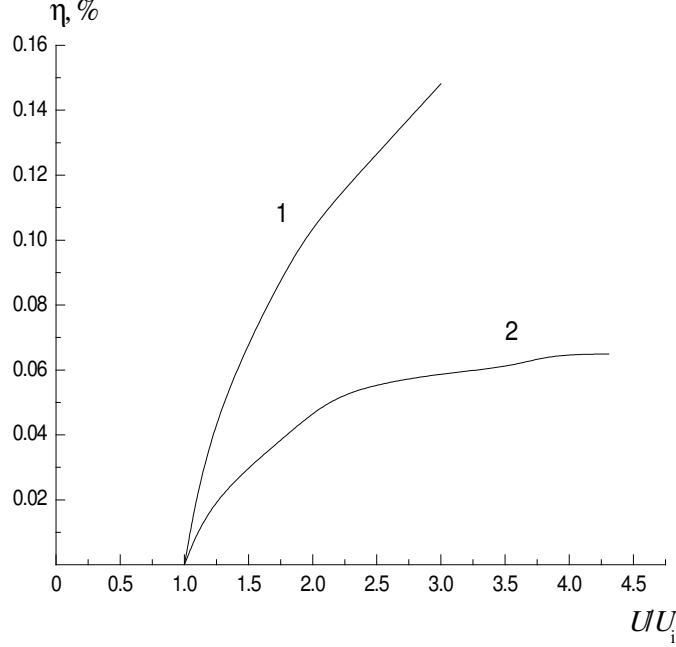


Figure 3: Energy efficiency as a function of the ratio of U voltage drop in contact to the starting voltage U_i : 1 — with Fe_3O_4 film, 2 — with Permalloy film.

4 Estimates of efficiency

Measurements of the voltage drop U in the magnetic junction and current I allow to evaluate the power released by the current $W_c = UI$ and the energy efficiency of the radiator $\eta \equiv W/W_c$, where W is the radiation power. Such efficiencies for two film types are shown in Fig. 3. The maximal efficiency reaches 0.15% with the magnetite film, and 0.06% with the Py film. The difference is due to different equilibrium spin polarization P that is about 0.4 for Py and is near to 1 for Fe_3O_4 [11]. Also, it should have in mind that magnetite is closer to semiconductor compounds, in its properties, than Py, so that larger spin diffusion length may be expected for magnetite [11]. Therefore, the interaction length of active spins with radiation may be larger, too, that leads to higher efficiency [10].

5 Influence of concentrator

There is a possibility to control the radiation power and energy efficiency by varying closing magnetic flux in the radiator [10]. The flux depends

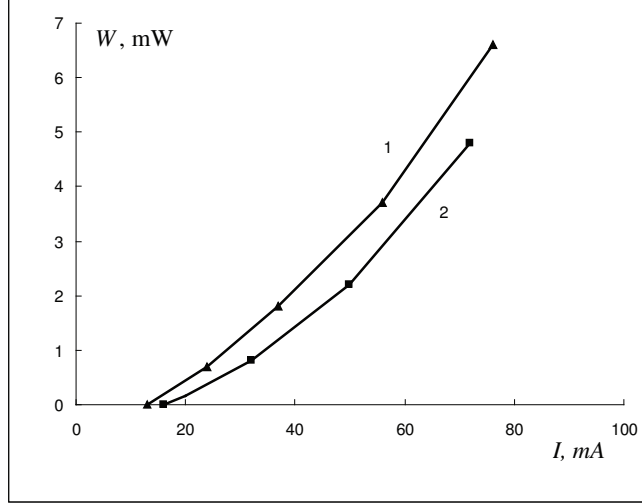


Figure 4: The concentrator effect on the radiating power in the structure with Fe_3O_4 film: 1 — with concentrator ($D = 1.5$ mm, $d = 1$ mm), 2 — without concentrator.

substantially on the magnetic core 11 under the substrate 3. The magnetic flux may be carried away from the sample completely with a layer of soft magnetic (transformer) steel. As a result, the spin-injection driven radiation disappears. It is possible, also, to enhance the radiation with such a magnetic core by concentrating the closing magnetic flux on the sample. For example, we made a magnetic concentrator in the form of a ring with diameter $D = 1.5$ mm of an iron wire with diameter $d = 1$ mm. The dependence of the radiation power on the current with using this concentrator is shown in Fig. 4. It is seen, that the concentrator decreases the starting current and leads to increasing the power under the same current value. The presented data are not optimal ones, they merely illustrate possible influence of concentrator.

The energy efficiency of the radiator with Fe_3O_4 film as a function of the ratio of the operating voltage to the starting one with and without concentrator is shown in Fig. 5. All the results indicate that the magnetic flux concentrator can enhance efficiency of forming negative spin polarization in the magnetic junction and increase the radiation power.

6 Quantum efficiency

Here, the quantum efficiency θ means the number of radiated photons per a current carrier. This quantity is interesting because it shows “radiative

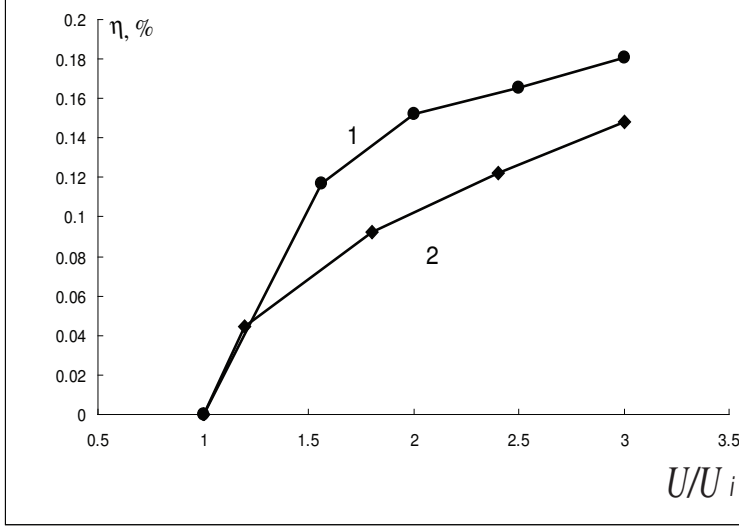


Figure 5: The energy efficiency of the radiator as a function of relative voltage drop in the contact U/U_i in the structure with Fe_3O_4 film: 1 — with concentrator ($D = 1.5$ mm, $d = 1$ mm), 2 — without concentrator.

capability” of the relaxation processes in the device and characterizes intensity of radiative processes. It can be calculate from experimental data as a ratio

$$\theta = \frac{W}{|I/e| \hbar \omega}, \quad (1)$$

where e is the electron charge, ω is the radiation angular frequency, \hbar is the Planck constant. By substituting to Eq. (1) the data for Fe_3O_4 from Fig. 3, namely, $W = 4.8$ mW, $I = 72$ mA, $\omega = 2\pi \times 10^{13} \text{ s}^{-1}$, we obtain $\theta \approx 1.7$.

Thus, the quantum efficiency appears to be more than unity. For the Py film, this parameter is lower, but may be close to unity. It should have in mind that non-radiative processes take place at room temperature. So, it may be concluded that a regular cause exists of the enhancement of the quantum efficiency. In our opinion, such enhancement may be due to substantial contribution of stimulated processes, which are induced by the electromagnetic energy stored in the radiator. The energy accumulation is a result of reflection the waves radiated earlier from the interfaces. It may be expected that placing the radiator into a selective resonator will amplify stimulated processes and lead to monochromatic coherent THz generation.

The spin-polarized current tends to sustain nonequilibrium spin distribution in the junction. Under such conditions, the stimulated radiative transitions add power to the spontaneous ones. This leads to enhancement of the quantum efficiency θ .

The stimulated transitions influences the dependence of the radiation

power on the current. It is seen from Fig. 3 that the power W depends almost quadratically on the current I . It should have in mind that 1) the current polarization is near to 100% ($P \approx 1$), and 2) the thermal contribution to power W is rather low in our conditions (it was shown in [10], that the power follows the current variations without inertia). In such a situation, the quadratical dependence on the current reflects coherent action of radiating spins, when the wave amplitudes are summed rather than powers.

7 Conclusions

In summary, we have evaluated the energy efficiency of the spin injection oscillator based on a ferromagnetic rod–film structure. It has been shown that

- The material choice influences substantially the efficiency. The magnetite films give higher efficiency than Permalloy ones.
- An additional element, namely, magnetic flux concentrator, has been proposed to improve efficiency.
- The quantum efficiency has been evaluated from the measurements, that appeared to be more than unity for magnetite films. This fact is interpreted as a manifestation of the stimulated radiative transitions.
- The stimulated transitions influence also the form of the current dependence of the power, which is close to quadratical one for the junction with magnetite film. Under low thermal contribution and 100% spin polarization, the quadratical dependence may be indication to coherent action of radiating spins with summation of the wave amplitudes

The work was supported by the Russian Foundation for Basic Research, Grants Nos. 10-02-00030-a and 10-07-00160-a.

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